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Two Cores Are Better Than One: predicting mixed-conifer growth in the Sierra Nevada

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Past radial growth of trees is a reliable index for predicting future stand growth. Although tree boles appear round, their cross sections are often irregular, and growth is asymmetrical. For this reason, more measurements increase the accuracy of prediction. A popular method of measurement is that of extracting one core per tree, although some investigators have recommended either one or two, and have even considered three cores as necessary. The choice has been made, however, without a statistical basis. Data were collected in 1978 from three species—white fir (*Abies concolor* [Gord. and Glend.] Lindl.), incense-cedar (*Libocedrus decurrens* Torr.), and ponderosa pine (*Pinus ponderosa* Laws.)—on the Eldorado National Forest in northern California. The results suggest that, when mixed conifers of the Sierra Nevada are considered as a group, more accurate predictions of growth can be made from two cores per tree.

Retrieval Terms: growth prediction, core drilling, mixed stands, *Abies concolor*, *Pinus ponderosa*, *Libocedrus decurrens*, Eldorado National Forest, Sierra Nevada.

Forest managers and inventory specialists need precise measurements to predict accurately stand growth, diameters of various species, and yields of natural stands. The increment core method is a popular technique whereby radial measurement, diameter of a tree at boring height, and age of the tree—both total age and age for an elapsed amount of growth—can be obtained.

Because cross sections of tree boles are often irregular—although they appear round—measures of radial increment will change around the bole circumference. This irregularity of the stem suggests that more than one core measurement may be desirable. Precise measurement is imperative because past diameters are reliable predictors of future ones. In fact, in a regression equation for lodgepole pine, diameter-at-breast-height (d.b.h.) alone contributed about two-thirds of the correlation.¹ Although a few investigators have considered the number of cores, and recommended either one or two, the choice has been made without a statistical basis.² Even three cores have been considered necessary, despite the manual labor required.³

Older methods of predicting growth—particularly traditional normal yield tables for even-aged stands—required fewer measurements. Modern simulation methods of stand and individual tree growth require more measurements for accurate

prediction of future growth. Because of the availability of high-speed computers at reasonable cost, an increase in numbers of measurements taken is feasible today.

This study was designed to predict growth of mixed-species, uneven-aged stands in the Sierra Nevada of northern California. Because an individual tree approach was required, several thousand trees were to be measured. The number of cores per tree necessary for accurate prediction, therefore, was a primary concern. Data from the first 830 trees we measured was used to answer the question: "Are two cores significantly better than one to justify the additional effort of taking two (or more) cores?"

The ratios of within- and between-tree variances for two cores per tree for the 830 trees measured from three mixed-conifer species suggests that, in the context of an individual tree-growth prediction model, two cores per tree will provide more accurate results than will one core.

METHODS

Data Collection

Data were collected in 1978 from widely scattered points on the Eldorado National Forest which extends westerly from Lake Tahoe, California, at 39°N. latitude. The mixed-conifer type covers the middle elevations, from about 2500 to 6500 feet, below red fir (*Abies magnifica* A. Murr) and lodgepole pine (*Pinus contorta* Dougl.), and above the drier foothill types. Trees were selected at random over a wide range of growing conditions. Three species were sampled in sufficient number to warrant statistical analysis: 494 white fir (*Abies concolor* [Gord. and Glend.] Lindl.), 215 incense-cedar (*Libocedrus decurrens* Torr.), and 121 ponderosa pine (*Pinus ponderosa* Laws.) trees. The live trees had to exceed 6 inches d.b.h. and be 80 years old or less because of the overall objective of predicting growth of young, mixed-conifer stands.

For each tree sampled, cores were taken at right angles to one another. If the shape at d.b.h. was judged to be elliptical, the first boring was the long axis and the second was at a right angle to the first. With round trees the initial boring was made at random. Each core's latest 10-year growth was measured with a ruler to the nearest 0.05 inch, sometimes using magnification, and recorded in the field.

Statistical Considerations

The past tree diameter is an independent variable in a least-squares framework for predicting future increment. That prediction, in turn, is the input value for the next growth prediction in a growth simulation program. This point is crucial because high variability in X-values means that the estimate of the coefficient is biased toward zero. The more cores per tree, the less the variance, and the closer we come to meeting the regression assumption of errorless measurement of the independent variable. With least-squares analysis, a rule-of-thumb is that the variance of X should be "... less than a tenth of the average scatter of the X's from their mean."⁵

It must be emphasized that the 10 percent rule-of-thumb is for the simplest case of *one* independent variable. Typically, one would expect growth prediction equations to include several independent variables, with likely candidates being either soil or site characteristics. The bias resulting from measurement error in soil variables when predicting growth has been shown in detail elsewhere.⁶ The certainty of at least two independent variables measured with error implies *halving* the 10 percent rule-of-thumb. We suggest that the within-tree variance should be less than 5 percent of the between-tree variance—a 5 percent rule-of-thumb. We are interested in the variance ratio for each species separately and for the group. The estimate of the pooled variance for all three species allows for the populations having different means and, therefore, avoids overestimating the variance.

The Variance Equation

Let X_{i1} be the long-axis, and X_{i2} the short axis, of the i th core. The within-tree variance is expressed as:

$$\sigma_1^2 = \sigma_{X_i}^2 = \sum_{i=1}^n (X_{i1} - X_{i2})^2 / 2n$$

$$\text{Let } \bar{X}_i = \frac{X_{i1} + X_{i2}}{2}$$

then the between-tree variance is:

$$\sigma_2^2 = \sigma_{\bar{X}_i}^2 = 2 \left[\frac{\sum_{i=1}^n \bar{X}_i^2 - \left(\sum_{i=1}^n \bar{X}_i \right)^2}{n} \right] / (n-1)$$

Table 1—Ratios of within-tree to between-tree variances for two cores per tree from each of three mixed-conifer species

Species	Variance ratio (σ_1^2/σ_2^2)	Trees	Decadal core length	
			Longest	Shortest
	Percent		Inches	
Ponderosa pine	4.7	121	2.4	0.1
Incense cedar	4.6	215	4.2	.1
White fir	7.0	494	3.5	.05
All	6.3	830	4.2	.05

RESULTS

The ratios of within-tree to between-tree variances for two cores per tree from each of three mixed-conifer species suggest that, in the matter of an individual tree-growth prediction model, two cores per tree will provide more accurate results than will one core (*table 1*).

The two species with the fewest observations—ponderosa pine and incense-cedar—have ratios nearly equal to each other and these ratios just fall within the 5 percent rule-of-thumb suggested. The larger number of white fir observations clearly supports the variance ratio of 7.0—a ratio markedly above those for other species. Measures of three cores would be needed to proportionally reduce the white fir ratio to 4.7 percent.

As another indication of variability, we should consider the maximum ratio of the longest core divided by the shortest, for any pair of cores. The maximum ratio, pair-wise, for ponderosa pine was 3.0:1, for incense cedar 2.2:1, and for white fir 7.5:1.

DISCUSSION

One core measurement of radial growth is sufficient in simple prediction cases and when moderate variability is present in a single independent variable in a regression framework. When the output of one prediction is the input for another, as in a tree growth simulator, then measurement error assumes greater importance. Because most growth equations will use at least two independent variables that are difficult to quantify, more measurements are recommended. As a general guide, a 5 percent rule-of-thumb is suggested for the case of two independent variables. In the complex case of uncertain measurement in several independent variables, no simple rule suffices.

In the context of an individual-tree growth prediction model, at least a pair of cores per tree are desirable.

NOTES

¹Cole, Dennis M., and Albert R. Stage. 1972. *Estimating future diameters of lodgepole pine trees*. USDA Forest Serv. Res. Paper INT-131, 20 p. Intermountain Forest and Range Exp. Stn., Ogden, Utah.

²Loetsch, F., F. Zohrer, and K. E. Haller. 1973. *Forest Inventory*. Vol. 11, p. 233. Blv. Verlagsgesellschaft, Munich.

³Wiley, Kenneth N. 1979. *Net and gross yields for natural stands of western hemlock in the Pacific Northwest*, p. 2. Weyerhaeuser For. Paper 19. Western Forestry Research Center, Weyerhaeuser Co., Centralia, Washington.

⁴Stage, Albert R. 1973. *Prognosis model for stand development*. USDA Forest Serv. Res. Paper INT-137, 32 p. Intermountain Forest and Range Exp. Stn., Ogden, Utah.

⁵Daniel, Cuthbert, and Fred Wood. 1971. *Fitting equations to data*, p. 32. Wiley-Interscience, New York.

⁶Lloyd, F. Thomas. 1978. *Choice of variables for correlation analysis when measurement error is present*. In *Proceedings Soil Moisture...Site Productivity Symposium* [Nov. 1-3, 1977, Myrtle Beach, S.C.], p. 292-295.

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